Lunar Precursor Robotic Program Mission
Constellation Dust Measurement Needs Assessment

December 21, 2006

Executive Summary

The Advanced Projects Office sponsored a meeting on November 30, 2006 to assess potential Constellation Program needs for a lunar robotic precursor mission to measure properties of dust prior to human lunar missions. Participants from GSFC, MSFC, GRC, JSC, ARC, and JPL represented the Lunar Curation Office, NESC Mechanical Systems Lunar Dust and Lunar Dust Safety Projects, the ETDP Dust Project, and Constellation Program's Advanced Projects Office, Test and Verification Office and Environments and Constraints SIG. The group discussed electrostatic characteristics, particle size distribution and reactivity to determine areas of consensus. A summary of the results follows.

Electrostatic: Electrostatic models predict changing electrical potentials above the surface as the day/night terminator sweeps across. This phenomenon, if true, may result in electrostatic shock to crew and equipment. Tribocharging (the process of creating a static electric charge on powder particles, in this case lunar dust, by friction against a non-conductive material) during surface activities may also lead to shocks. Very little is known about the electrostatic environment and the group agreed that measuring voltage potential at varying heights above the surface is needed.

Particle Size Distribution: The group agreed that samples returned during Apollo were sufficient for further characterization of intrinsic particle size and distribution. This information is important to the toxicology community in establishing inhalation standards and Constellation designers in developing robust and reliable systems.

Reactivity: For toxicology, studies are currently being planned to activate samples returned during Apollo by breaking bonds with radiation bombardment. The activated samples will be measured to determine the reaction time. This information will allow the toxicological community to establish standards for human inhalation. (Note: Toxicologists and Flight Medicine have expressed a need, to the Lunar Precursor Robotics Program, for a lunar precursor mission to measure reactivity of the finest fraction of lunar dust. Follow-on discussions are described below).

To assess the potential for damage that might be caused by dust interaction with surfaces the group agreed that further study is needed, including studies on the Surveyor III camera and review of Apollo Lunar Science Experiment Package data to determine if any damage due to reaction between lunar dust and surfaces was observed. Tests using our most pristine lunar samples may also provide insight into the question of reactivity. This information may be important to designers of external surface systems exposed to lunar dust.

Background

The Johnson Space Center's Crew and Thermal Systems Division performed an assessment of system effects due to exposure to lunar dust. The report, "**An Assessment of Dust Effects on Planetary Surface Systems to Support Exploration Requirements,**" was published internally on August 20, 2004 and as a NASA Technical Paper, NASA/TM-2006-213722, in 2006.

The multi-center, multi-discipline study assessed the effects of lunar and Martian dust on human support systems, the properties of planetary dust that system designers need to understand to design systems that can tolerate the dusty environments that will be encountered as NASA embarks on its Vision for Space Exploration, and determined what data is known, what characteristics needed further research, and what data could only be obtained in-situ. The boundary for the assessment was defined within the red dashed line in Figure 1.

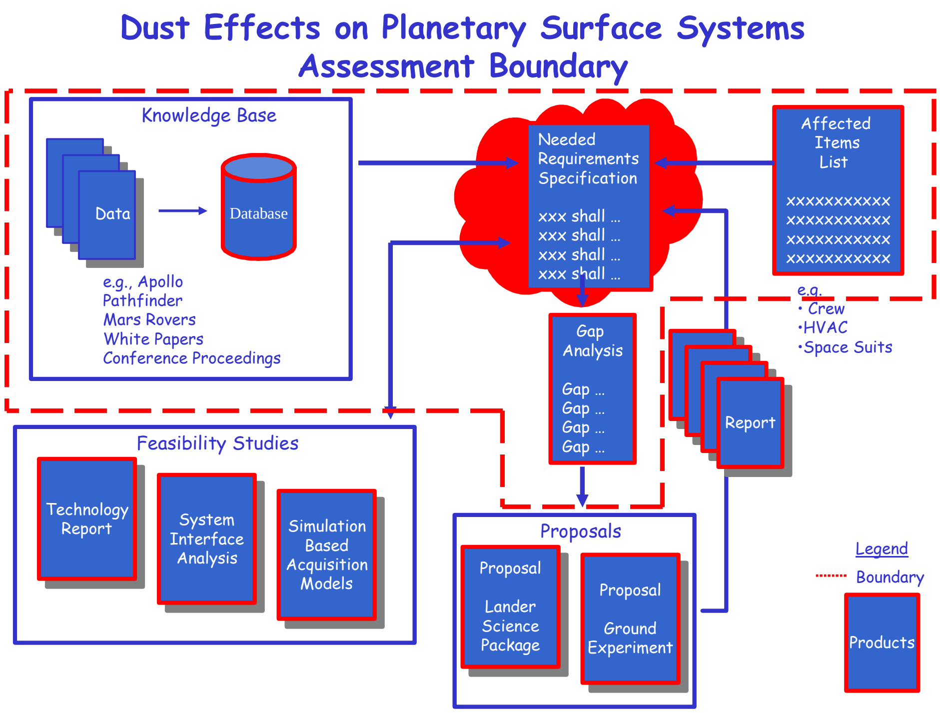

Figure 1

Forty-seven participants representing extracurricular activity, life support modeling, habitat, airlock, sensors, air, water, waste, power, fire detection and suppression, food, the astromaterials curation office, in-situ resource utilization, mechanical, industrial hygiene, safety and mission assurance, astronaut office, mission operations, human factors, toxicology, research and technology development, technology integration, and flight surgeons participated in the assessment. Members from Ames Research Center, Glenn Research Center, Johnson Space Center, Kennedy Space Center and the Colorado School of Mines participated in meetings and provided input to the assessment.

The assessment included a spreadsheet that catalogued system, subsystem, component, effects on system, risk assessment, requirements needed, knowledge gaps, and recommendations for dust characterization on the Earth, the Moon and Mars. This spreadsheet is included as Appendix A.

Methodology

The Lunar Precursor Robotic Program Mission Constellation Dust Measurement Needs Assessment built on the work performed in the assessment described above to develop a recommendation for potential lunar dust measurements that the Constellation Program may need in order to develop dust tolerant systems.

A new, summary spreadsheet, using data from the spreadsheet developed for the earlier assessment, was generated. This spreadsheet includes the affected system, characteristic of interest, factor in design, lunar materials curator's knowledge gap assessment and Lunar Precursor Robotic Program mission recommendation columns and is included as Appendix B.

Core team members of the 2004 assessment reviewed and commented on the new spreadsheet. Some of the comments were in conflict, so the Advanced Projects Office sponsored a Science Focused Comment Resolution Meeting on November 30, 2006 to determine areas of consensus, as well as, to identify specific areas of disagreement.

Note: The primary focus of this activity is to determine if in-situ lunar dust measurement is needed prior to human lunar missions. Many comments added information that was not included in the earlier assessment. That assessment is not scheduled to be updated; however, all comments received are included in Appendix C for completeness.

The majority of conflicting comments related to characteristics of interest; electrostatics, particle size distribution, reactivity and integrated environment. The meeting was divided into four seventy-five minute sessions to discuss each.

- 3 Lunar Dust Electrostatics comments
- 4 Lunar Dust Particle Size comments
- 3 Lunar Dust Reactivity comments
- 5 Integrated Lunar Environment comments

The meeting included an overview of important considerations to remember during the discussions:

Purpose: Does CxP need in-situ dust measurements prior to a human lunar mission?
Scope:
- What lunar dust data do CxP engineers need to develop their systems?
- Does the data currently exist?

- Can knowledge gaps be filled by studying materials returned during Apollo, other analysis, simulation or modeling?
- Is the data needed prior to the first mission?

Considerations:
- Many competing objectives for limited number of LPRP missions
- Dust mitigation technology projects must achieve TRL 6 prior to CxPO need dates

Two Questions – Meeting should concentrate on the second question:
- What lunar dust data do engineers need to design their systems?
- Does the knowledge require in-situ measurement?

The product from the meeting was a completed Assessment Comments and Disposition Spreadsheet and is summarized in the next section of this report. The spreadsheet contains columns for comment, commenter, resolution/rationale, meeting notes, session and meeting consensus. The comment, commenter and session were completed prior to the meeting. The other columns were used during the meeting to capture the discussions. This format worked well during the meeting; however, the next section of this report contains a more readable form.

Note: The ETDP ISRU project is currently working on a precursor mission for technology demonstration. Some measurements may also be performed in conjunction with the demonstration. Because this work is ongoing, this assessment did not address ISRU. The ETDP ISRU project manager did provide input that indicated a need for a precursor measurement of the electrostatic characteristics of lunar dust.

Meeting Notes

Attendees:

Bill Farrell	GSFC	Dusty Plasma
Phillip Abel	GRC	ETDP Technical Lead
David McKay	JSC	Astromaterials
Arnon Chait	GRC	Electrostatics
Paul Greenberg	GRC	Particle Size Distribution/Sensors
Dean Eppler	JSC	CxP, APO Science Advisor
Gary Lofgren	JSC	Lunar Curation
Carlton Allen	JSC	Astromaterials Curator
Mark Hyatt	GRC	ETDP Project Manager
George Xenofos	JSC	CxP, Test and Verification
Mike Boulavsky	JSC	CxP, Test and Verification
John Tatum	JSC	Crew and Thermal Systems Division
Ed Strong	JSC	CxP, Test and Verification
John Lindsay	LPI	Sedimentologist
Andy Thomas	JSC	Astronaut
Chris Gerty	JSC	CxP, ARDIG
John Feighery	JSC	ETDP Deputy Project Manager

John McManamen	JSC	NESC
Mike Sims	ARC	NESC
Rob Suggs	MSFC	CxP, Environments and Constraints SIG
Dan Winterhalter	JPL	NESC

<u>Meeting Discussion</u>

Particle Size Distribution

For the purposes of this meeting the questions to answer are: 1) Are more measurements needed on particle size distribution and 2) Is there enough lunar dust on Earth to perform any needed measurements?

Some in the meeting expressed that it is important to understand the particle shape of smaller particles. Grain size is critical for setting toxicology standards as well as for the protecting mechanical equipment. Requirements may have grain size specified so the work needs to be done soon. Lunar material is well characterized except for the <20 μm. The Lunar Curator has samples that can be used to characterize this small fraction. The question arose if there are enough of these particles in the available samples to test the effective size distribution.

Filters, suits and vacuums at the JSC and the Smithsonian's National Air and Space Museum are being examined now to determine the particle size distribution that was transported into the Lunar Module during Apollo surface operations. The smallest dust particles found are 10-20 μm and believe that that particles > 40 μm fall off the suit and smaller particles will stick, however, that needs to be verified. Some stated that if dust has not adhered to a surface we don't care about it. Others reminded the group that during Apollo, it was the dust that fell off the equipment, samples, suits, etc. that contaminated the Lunar and Command Modules and that pebbles and rocks were a concern as well.

The question was asked, was there anything identified during Apollo related to dust problems that require more knowledge of grain size distribution? No one at the meeting was aware of any Apollo reports of problems associated with grain size.

The lunar dust samples taken during Apollo were taken during daylight and not at night. It would be nice to have particle distribution vs. height (relevant size distribution). This discussion was the result of the hypothesized dusty plasma phenomenon often used to explain LEAM experiment anomalies.

Also, the samples were not taken from the South Pole. Questions arose relating to the state of our knowledge of grain size distribution, loose dust and permafrost at the South Pole. Little data exists on South Pole regolith. LRO will collect image data to help is understand crater morphology. The Lunar Materials Curator stated that lunar dust at Polar Regions would not be different in composition from dust in equatorial regions. If water is in permanently shadowed areas, grain size would be larger and grains less reactive than at the equator.

Some in the group discussed the appropriateness of the intrinsic (surface) particle size distribution for assessing dust effects. It was pointed out that the actual entrained size distribution found on suits, equipment, etc. and the size distribution that is expected to be brought into the habitat is a fraction of the intrinsic distribution. Determination of the actual fraction is complex and is a function of multiple physical forces such as electrostatic levitation, adherence, etc. However, the entire group reached consensus that samples returned during Apollo were sufficient to further characterize particle size and distribution.

Electrostatic

The discussion of electrostatic properties of lunar dust fell into three categories; 1) Predicted phenomena such as tribocharging or differential plasma interactions resulting in potential differences between mission assets, including crew that could result in electric shock; adhesion of dust on surfaces; and levitation and dusty plasma that could result in damage to mission assets.

Tribocharging

The question was asked as to the level of confidence in our models and what uncertainty exists in the parameters in the model. A suggestion was made that engineers already internally ground between spacecraft to reduce the risk of electric potential differences. The risks associated with tribocharging may be addressed in the same fashion. Possible forward work should be performed by engineering with respect to grounding.

Grounding is a significant issue as far as design of mechanical or electrical systems. Measurements could be performed during a precursor mission to reduce uncertainty in the model. Determining the potential difference between the lander relative to overall system may be difficult.

A suggestion was made to review Apollo documents to determine if there is any evidence of unexpected telemetry or damage due to tribocharging and if it was occurring why it was not detected. There were no references to dust related effects, however, review of mission telemetry may show indications of tribocharging.

A suggestion was also made that the spacesuit is analogous to a capacitor and it would be possible to detect charge level as the crew member moves about the lunar surface. This type of instrument is not complicated and not expensive.

<u>*Levitation, Transport and Dusty Plasma*</u>

Some expressed a need to measure the plasma flow, i.e. moving particles to determine what parameters affect dust transport and adhesion as some models suggest charged particle magnetic fields. Terminator and night side modeling may be needed.

A suggestion was made to measure plasma parameters specifically at various locations, such as near the South Pole, and during anticipated events, such as during the passing of the terminator, on the dark side, and during the passing of the earth wake. These parameters serve as inputs to dusty plasma models for predicting dust interaction and electrical effects.

The question was asked if this measurement needs to be performed before we go back to moon. Since NASA only has had human presence during the lunar day, a suggestion was made to limit EVA to daytime only and restrict operations during the terminator to reduce risk until the plasma could be measured. Could the plasma fields in the terminator measurements be made during the early missions?

There may be critical equipment outside of the pressurized habitat such as power generation that might be damaged by exposure to the dusty plasma. Models predict and some data exists from the LEAM experiment that dust may travel at 500 m/s. This would indicate there would be a specific preferential distribution of particles. If this is true it should be possible to measure a size selection process and if so if it is affected by altitude.

Some in the meeting were skeptical of the models. There is no evidence of large scale movement of dust over time. In particular, the persistence of defined compositional and albedo boundaries over several billion years argues against long scape transport of regolith. Rocks were clean of dust. If dust were moving with every terminator, there should be dust on the rocks.

The question was asked if there has been an attempt to model the movement of lunar dust across the surface and, if so, if enough is known about how much is moving around to make the model. This needs to be modeled using available data.

LEAM was designed to measure ejecta from micro meteor strikes. The experiment was powered off during the day due to overheating caused by the crew inadvertently contaminating the thermal surfaces with dust. Anomalous telemetry was explained by dusty plasma models. The dust flux, as a function of energy, may validate LEAM data. However, the LEAM was not designed to measure dust and the question was raised as to whether the LEAM was capable of measuring dust.

The group agreed that analysis of data packages from Apollo may help to determine if any degradation was caused by dust falling onto equipment during terminator cycles that may have degraded instrumentation. Some members of the group asked why the optical performance of retro-reflectors from the laser ranging experiments have not degraded significantly over the past 35 years. Small changes might not be detectable since the earth bound instruments have improved markedly over time, but it seems that a significant covering by dust would have been detected.

Adherence

The ETDP Dust Project is performing analyses to follow lunar dust through system - boots-suits-vehicle and have observed that the particle size cuts off at 40 μm (what stuck to the suit and what the vacuum took off). There were few particles larger than 40 μm.

Longer surface stays and different mission operational scenarios may lead to transport adhesion being dominated by electrostatics and may lead to a need to engineer systems to repel and clean dust from surfaces. Citing the dust on EVA suits, some believe that designing systems that can be assembled and disassembled is not possible without a better understanding of lunar dust electrostatic characteristics. However, it was pointed out that the Apollo astronauts got dirty, not because electrostatics caused the dust to adhere to the suit, but because they were rolling around in it.

Consensus Opinion

The group agreed that we do not understand the in-situ electrostatic nature of lunar dust very well. Some systems may be delivered on the earliest Sorties. There was a consensus that we have uncertainty in the data and we should ensure we can retrofit, clean, etc. by scarring so it can be incrementally be build in.

The group agreed that the highest priority for a dust measurement by a precursor mission was to measure the potential difference at various heights above the surface, 5 to 10 meters. A simple probe (perhaps similar to a Langmuir type probe) could easily be placed on a spacecraft and measure these differences. The probe should be placed at a location representative of the human lunar destination.

The Langmuir probe actually measures plasma current, and hence, is not an ideal system to make this measurement. This recommendation does not recommend a particular probe. Also, in reality a lunar lander will probably not be able to deploy a 10 meter mast to make these measurements, as it may drive the architecture. A measurement up to the first meter or so may be more realistic.

Reactivity

Reactivity was defined as the presence of free bonds on the surface of the lunar dust grains. The toxicological community needs to know how long it takes lunar dust to satisfy its bonds after entering the habitable atmosphere in order to develop its inhalation standard. Lunar samples are at all stages of reactivity that can be studied to plot what is changing. The hydrogen peroxide test could be done on the moon to determine reactivity.

Earth based experiments are planned to activate lunar dust using radiation then measure the length of time it takes for the dust to satisfy its bonds. There is a small subset of lunar samples that may be reactive. However, some suggest a range of exposure histories is needed to look for a trend.

The other aspect is the in-situ reactivity that surface systems will be exposed to. Determining the sticking coefficient may be useful to determine potential damage to surfaces that may be caused by exposure to reactive lunar dust. For example, if a radiator system with highly reactive dust adhering, may not be able to be cleaned even with a duster. A test with an atomic force microscope that will measure how tightly a grain sticks may provide additional information on this subject. Reactivity may change the characteristics of surfaces. Examination of the Surveyor III camera might provide answers by performing a study of dust interactions under a microscope. There is evidence of discoloration on surfaces in aluminum, camera lenses, and some painted surfaces with a two year exposure. There are several papers written in the 1970s about the analysis of returned Surveyor parts. For example, there is a paper by Blair, Carroll, Jacobs and Leger from the AIAA 6th Thermophysics Conference in 19721, "Study of Thermal Control Surfaces Returned from Surveyor III. In the reference list for this paper are two others, one examining the scoop and another on the discoloration and dust contamination of the Surveyor III surfaces. The historical record should be reviewed and more detailed analysis of Surveyor III parts is needed to determine the cause of the discoloration. The Apollo 12 Technical Debrief contains a quote that the discoloration could be removed by rubbing the surface and the Mission Report speculates the discoloration could be caused by dust, radiation or some other mechanism.

For toxicology, the group agreed that the planned studies to activate lunar dust and measure reactivity should be sufficient and that a lunar precursor mission was not necessary.

Note: The LADTAG developed the following consensus statement:

> We met at JSC on 9/5/06 and discussed human toxicology priorities for LPRP. Attending the meeting: John James, Noreen Khan, Antony Jeevarajan, and Rick McCluskey. We worked out a consensus of what characteristics of polar lunar soil we are most interested in. The following list is not prioritized and not screened for engineering feasibility. I presume that the RFP process will determine feasibility.
>
> **We are interested in lunar material with the following characteristics:**
>
> **1 soil particles < 10 um diameter**
>
> *rationale: Acute human toxicity in the habitat will be mostly associated with inhaled dust. The respirable range for dust particles is less than 10 um.*
>
> **2 soil collected within 2 cm of the surface**
>
> *rationale: "Activation" of the dust to a reactive state, if it occurs, would most likely be due to exposure to sunlight and solar wind. Unexposed soil from below the "gardening" zone, would not be relevant. The dust most likely to be brought into the habitat during routine EVAs is from the topmost layer.*
>
> **3 samples not contaminated by propellant**

4 half of the samples would be from predominantly dark areas and half from predominantly sunlight illuminated areas, with 3-5 sample in each
rationale: Sunlight likely plays an important role in "activation" of the dust, if activation occurs. Comparing sunlight exposed to sunlight unexposed areas would help discriminate sunlight from solar wind-induced processes as a causative factor.

<u>What we want to know about the material described above:</u>
Physical characteristics
1 size distribution and particle morphology (shape, aspect ratio, surface area, crystallinity) for dust particles between 0.5 and 10 um diameter
rationale: Particle size and morphology are critical factors in pulmonary toxicity. Lunar dust in the respirable range (<10 um) has not been well characterized. We can study Apollo archive dust from the equator/mare, but need a baseline for polar/highland material for comparison.

Chemical properties
2 bulk charge properties and bulk magnetic properties (magnetic moment per gram)
rationale: These properties may be different from the larger particles that have been studied. Determining the charge and magnetic properties of the dust will help us understand the potential for the dust particles to aggregate and increase or decrease the exposure or toxicity. These properties may also be an important consideration in designing countermeasures for this fine dust.

3 chemical reactivity of lunar dust- bulk oxidation capacity and potential for radical production in an aqueous system
rationale: Acute toxicity significantly depends on the production of reactive species in the aqueous environment of the lungs. Production of strongly oxidizing species or free radicals would indicate that the dust is acutely toxic.

4 passivation of dust in a habitable environment
rationale: If the dust is shown to be "activated" in its native state on the lunar surface, then the rate of "passivation" when it is brought into the moist oxygen/nitrogen habitat will be an important consideration in assessing the risk associated with its toxicity.

In subsequent conversations with the LADTAG the toxicological and medical communities have gained more confidence in the state of knowledge of lunar dust and the ability to simulate reactivity of lunar dust in Earth based laboratories. Consequently, the current position is that a lunar precursor mission is not required prior to human missions. However, obtaining in-situ measurements would reduce uncertainty in the human inhalation standard and possibly reduce the conservatism built into the limits due to increased confidence in knowledge.

For interaction with surfaces the group suggested that study of the Surveyor III parts and other materials returned during Apollo would be useful. At this point it doesn't appear a robotic mission on the surface is necessary for samples or data. However further study should be done promptly because designs are in work now for equipment that will remain on the surface for long duration. There is a surveyor in the Smithsonian that has never left earth that might be used for comparison.

Integrated Environment

Some of the group expressed the thought that the fundamental issue at play here concerns the inherent and inseparable coupling between dust and its environment and noted a need to measure in-situ the size vs. charge state distributions of suspended particulates. In this context, suspension of material can arise via either natural phenomena, or suitably simulated anthropogenic perturbations. In a viscous-free environment, all transport is mediated by electrostatics. However, due to uncertainties in the coupling parameters in the plasma models, the actual in-situ charge state of suspended particles is not well known. Measurement would provide additional value insofar as providing data required to validate the models and quantify critical coefficients. The charging efficiencies associated with tribocharging processes are even less certain, and can only be determined experimentally.

<u>Lunar Dust Activities</u>

The Director, Constellation Program, Advanced Projects Office requested a compilation of lunar dust activities across the agency. Appendix D provides those known by the author. This list may grow as more activities are identified.